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Development of Methodology for Lifetime Calculation for Axial Piston Units.

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Abstract— **The need for improvement of lifetime prediction of hydrostatic axial piston units is driven by partly outdated knowledge dating back to the 1970s and is also motivated by a significant evolution of hydrostatic drivetrains. However, the evolution of the load life is unknown and must be investigated. An additional aspect for the method improvement is the potential decrease of qualification effort caused by required evaluation background. The goal is an increase in the prediction accuracy of the lifetime by using of qualitative and quantitative calculation methods. This paper covers the analysis phase of the lifetime calculation improvement. Hence, the currently used calculation method is investigated and the improvement potential builds the research approach. The improvement potential covers calculation model of load-dependent treatment, where the characteristics of sub-components build a system assessment. The aim includes the representative load cycle acquisition for typical applications in the off-road market.**

Keywords—pump; motor; field; clustering; lifetime prediction; load cycle; drivetrain; distribution

I. Motivation And Introduction

The lifetime of the axial piston units (pump and motor) must be analyzed due to the fact that the existing methods deliver results with insufficient accuracy. Additional, the calculation results have to be verified by time-consuming testing. The assumption is that the currently-used methods are in need of improvement. Two different aspects confirm this: the first aspect is the vehicle evolution in field and the second is the engineering progress in case of data acquisition. The evolution of the off-road applications changed the demands for the drive system suppliers. Hence, the providing of a greater accuracy in lifetime prediction is required. Whilst, the scientific progress gives the possibility of new engineering tools, scientific methods and data acquisition concepts.

A closer look into the field of study of the lifetime calculation shows the strong influence by bearing studies. This is not surprising since the main components of axial piston units are the bearings, the rotating group (also called kit) and the shaft. Due to the similar behavior of the kit and shaft, compared to the bearing subcomponents, the transfer of the bearing knowledge was an obvious assumption in the past. However, during the last decades the bearing research has continuously progressed in scientific field of the lifetime calculation, whilst the lifetime research of axial piston units got stuck in the end of 1970s. The investigation of the publications and literature shows the missing scientific focus on lifetime accuracy, but a high focus on developing the performance and effectiveness of drivetrain components.

But, the area of the lifetime research is slowly receiving a higher level of attention, in the last decade. Different approaches already exist like, "to increase the operation life of drivetrains based on load cycle determination and fault detection", [1]. The mentioned work and others like "real-time estimation of the remaining lifetime of drivetrain components" are focused on the increasing or improving of operative availability, [2], which do support the treatment of the lifetime prediction and has an emphasis on product yield. The different scientific approaches attack the lifetime (also called operative availability) by splitting of a specific topic like wear or gap analysis to simplify the problem. The overall study of the lifetime calculation is difficult due to many influencing factors, such as: load, temperature, cleanliness, design influence, etc. The knowledge gap of the lifetime prediction of axial piston units has been growing because the evolution of off-road application has advanced significantly in the meantime [3], [4].

As described above the bearings field got decisive impulses different researched areas, which can be partly applied to the axial piston units as well. Already in the early 1980s, bearing scientists studied the dependency factors of the load life to the bearing design. Thus, the analysis includes factors of bearing design and cleanliness. The most important conclusion was that the load life behavior of the bearings is fundamentally different than previously assumed [5]. It is also known that, in some ideal cases of sliding friction; i.e. journal bearings, the bearings are failsafe due to their high fatigue resistance when a minimum oil film thickness is maintained. The aspects of the fatigue resistance and load life independency lead to the approach that the simple equation of lifetime $L = (C/P)^k$ is insufficient to get the needed accuracy of calculated results. Where, L is the predicted lifetime, C is the basic dynamic load rating, P is the equivalent dynamic load and k is the specific lifetime exponent.

However, the real lifetime is dependent on many factors like mixed friction, oil quality, wear model, etc. Thus, a broader approach of prediction is needed. According to Lorösch's statement, the extended calculation of rolling bearings showed, already in 1980s, that the previous design of bearings was

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oversized [6]. The effect of the oversizing can be expected with axial piston units as well, since the field observation shows units that exhibit a theoretically endless lifetime, caused by fatigue resistance. The consequences of the oversizing are becoming more important, with relation to the cost as well as the reduced energy efficiency of the drive system. The subsequent unprofitability and inefficiency of modern products is a “no go” in todays’ market.

This paper is the first part of a study series around the improvement of the lifetime calculation method. In general, the series will address the knowledge gap between available methods and real unit lifetime, described above. While the objective is to deliver a revision of the existing methods of lifetime calculation for hydrostatic axial piston units. Based on an analysis of current methods, a more accurate and reliable prediction method will be derived. Thus, a load chain will be built as a calculation model, [7]. The approach of the effect chain is covered by the “Addressing of issues”-section. Wherever, the calculation model will deliver a new possibility of sub-component analysis. Hence, a reliability of the system or component and the probability of the failures will be analyzed in regard to unit design and operation cycles as well as failure modes. A key part of the study series will be experimental validation of the methodology, to evaluate the reliability and accuracy of the new results. In this section of the study series, the load spectrum investigation is in focus as well. Especially the purpose to introduce an offline investigation method as a post process analysis for the load rate of axial piston units, using the in field-created load spectrum is in focus.

The known load spectrum provides the possibility to meet the development goals more effectively. In this case, aspects like known propel load specification help to avoid disadvantages like underestimation or overestimation. A unit design which is more tailored leads to products that are more energy and cost efficient. Within this paper, an approach for the fundamental data core for the lifetime calculation is shortly introduced as well.

The paper is divided into three primary sections:

1. “State of the art” and “Key-components”
2. “Addressing of the issues”
3. “Conclusion” and “Outlook”

The study of the current calculation methods is done and will be introduced in this paper. Thus, different common statistic and numeric methods are investigated and will be used for the new prediction approach. The accuracy limits of current lifetime calculation are shown in the “Addressing of the Issues” section. After a conclusion, the outlook describes the next steps of the study series.

II. State Of The Art

Current lifetime prediction is characterized by quantitative distribution methods and the availability of load data. This includes the quantitative methods and standard load testing only. Only in specific or rare cases does a complete load to life relationship exist that can be used for a prediction. Based on experience and testing, different methods like Miner’s Rule or Weibull’s Theory are used. The choice of the method is connected to different factors. For example, the Weibull distribution can be used if some failure rate data is available, whereas the WeiBayes method is an alternative way to predict the lifetime without any existing failure rate data. The approach of most calculation tools is based on the assumption, that all moving subcomponents of an axial piston unit are affected by overall fatigue. This assumption is partly correct, but some different factors are not included. The most expected failure of a rotating group is the wear out, but the dynamic load chain inside of an assembly can have different impact on different subcomponents. This is not considered in an overall view. The possibility to measure the wear does exist in different forms like dimension measurement of wear-affected components, flow loss or temperature increasing.

To make the limited capabilities of current calculation methods more visible, the following calculation example is used. Miner’s rule is one of the most widely used cumulative damage models for failures caused by fatigue. Popularized by M. A. Miner in 1945, [8]. Miner’s rule is probably the simplest cumulative damage model and is called the Linear Damage Rule as well. The linear assumption can be done for one component only. The system view can be an accumulation of different component curves. Failure is predicted to occur when:

$$X = \sum_{i=1}^{I} D_i \tag{2.1}$$

Where, i is defined as the counter of system subcomponents, X = damage criterion and the damage fraction D_i is defined as the fraction of life used up by an event or a series of events.

The Miner’s Rule states that the damage fraction, at a given constant stress level, is equal to the number of applied cycles n at a stress level divided by the fatigue life N at specified stress level. For Miner's Rule, the damage criterion X is assumed to be equal to 1, and failure is predicted not to occur when:

$$\sum_{i=1}^{I} D_i = \sum_{i=1}^{I} \frac{n_i}{N_i} \leq 1 \tag{2.2}$$

Where, n_i = number of applied cycles at constant stress level and N_i = fatigue life at constant stress level

In simpler terms, the Miner’s Rule described the fatigue limit of a component or system life. Hence, exceeding the Wöhler curve is equal to end of life. The Miner’s Rule is applicable to fatigue observation with linear life limitation. The illustration in figure 1 show an example of field data with subsequent data analyzation according to Miner’s Rule.

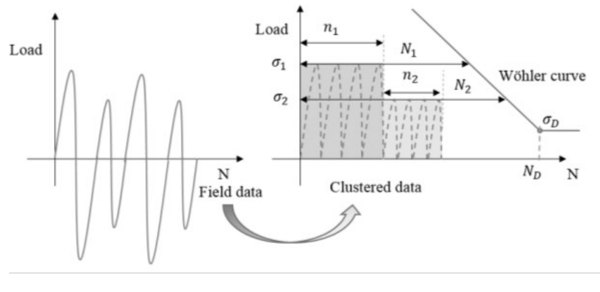

Fig. 1. Miner’s Rule & Wöhler curve

With a known lifetime exponent k of the Wöhler curve it is possible to calculate the End of Life (N_{EOL}) with the following equation, [9]:

$$N_{EOL} = \frac{\sum_{i=1}^{I} n_i}{\sum_{i=1}^{I} \frac{n_i}{N_D}\left(\frac{\sigma_i}{\sigma_D}\right)^k} \tag{2.3}$$

Where, σ_i = stress/load on constant level and σ_D = load on the fatigue resistance point. N_D = cycles to fatigue resistance point and n_i = number of applied cycles at constant stress level.

The complex failure structure requires extended approaches. Since Lorösch [6] and other different publications like the work of Zaretsky [10], documented that the lifetime depends on many other factors than just fatigue effects.

To have an overview of common lifetime calculations, the common "state of the art"-methods (used in the area of lifetime calculation of drivetrains) are shown in this paper. The investigation does cover the mathematical and statistical distributions mostly used in reliability calculation of the lifetime. Among others the reliability function, cumulative distribution function, probability distribution function, hazard function and the bathtub curve concept are studied. These functions are used to calculate the failure distributions and predict reliability lifetimes. Reliability is the probability of the product performing properly under typical operating conditions for the expected lifetime intended, and an expression to define reliability is, [11]:

$$R(t) = 1 - f(t) \tag{2.4}$$

Here, $R(t)$ is the reliability function, which is defined as the probability of operating without failure to time t. $f(t)$ is the cumulative failure distribution function. In reliability, $f(t)$ is the probability that a randomly chosen part will fail by time t, [12].

Many different distribution methods and techniques are already existing, including quantitative methods and qualitative approaches. In the following section the focus will be on methods that are mostly used in today's drivetrains environment. First of all, it is important to understand the development and the continuous spreading of the hazard of different failure types:

A. *Hazard functions*

The hazard scenarios commonly used today are of enormous value to the investigation. It is important to be able to specify the failure characteristic. The most common hazard functions are the following [13]:

1. Increasing failure rate (IFR): here it is expected to see an increasing rate of failures for given periods of time. The IFR is characteristic for fatigue effects and is typically used for lifetime calculations of axial piston units.
2. Decreasing failure rate (DFR): here it is expected to see a decreasing rate of failures for given periods of time. This behavior is typical for new products with design or specification failures. This characteristic will be analyzed in more depth during the fault tree analysis (FTA) in one of the following sequels of this work.
3. Constant failure rate (CFR): here it is expected to see a constant number of failures for given periods of time. This characteristic covers random failures without any connection to predicted lifetime. The random classification is often used for unexpected failure and will be researched as well
4. Bathtub curve combine the three previous described failure rates together to a life period curve. A complex product with different functions / characteristics (mechanical, electronical and chemical) can theoretically pass all three periods of the bathtub curve.

B. *Quantitative methods:*

The empirical probability-based modeling of a system opens a way out of the dilemma of the combinatorial explosion, which limits qualitative methods. The basic idea is to empirically capture a system and derive functional relationships from extracted data.

The Weibull Distribution

The Weibull distribution is a general-purpose reliability distribution used to model material strength, times-to-failure of electronic and mechanical components, equipment or systems. In its most general case, the 3-parameter Weibull probability density function (PDF) is defined by [14]:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \cdot e^{-(\frac{t-\gamma}{\eta})\beta} \tag{2.7}$$

Where β = shape parameter (Weibull's slope), η = scale parameter and γ = location parameter.

WeiBayes

The WeiBayes method is defined as Weibull analysis using a previously estimated shape parameter β. It was developed to perform Weibull analyzes based on very small samples or without any failure data. Zero failure tests: A minimum characteristic life time to be demonstrated [12, 15]:

$$f(t) = \left(\frac{\sum_i^N t_i^\beta}{-\ln(1-C)}\right)^{1/\beta} \tag{2.8}$$

Where C = confidence factor

Lundberg-Palmgren

In 1947, Lundberg and Palmgren used the Weibull probability distribution of metallic fatigue of 1939 to develop the basic theory of stochastic distribution of bearing life according to the equation below, [16]:

$$f(x) = \frac{\tau^c \eta^e}{z^h} \tag{2.9}$$

Where τ = orthogonal shear stress, η = life and z = depth to the maximum orthogonal shear stress.

C. *Qualitative methods*

The qualitative method usually takes the form of an investigation, experience sharing or inspection. For example, the method includes the compliance with generally accepted rules and regulations (best practices) for handling or processes. In addition to technical aspects, process sequences can also be recorded and evaluated. In the assessment of the recorded data, the knowledge about the functional relationship of internal processes and processes of the system under investigation is primary used.

The error analysis is used to identify failure mechanisms or causes of a system and to indicate the failure effects. Failure analysis and reliability modeling are processes which deliver the qualitative basis for determining quantitative reliability measures. Since, the FMEA covers the analysis of a system from bottom to top, the overview makes it difficult to see the effect a component failure mode has on the system. The improved overview can be achieved by FTA analysis, [17].

FMEA

The FMEA identifies and prioritizes risks and identifies corrective actions. This method covers analytical as well as qualitative aspects. Thus, errors are assessed according to the frequency of their occurrence, their detection and the severity of their consequences. The term “failure mode” describe an error which can occur in a system. The effect analysis shows the consequences of these errors. The FMEA is typically used during the design phase of a system to prevent future errors.

Fault Tree Analysis (FTA):

The fault tree analysis covers the failure propagation in the reverse direction compared to the FMEA. Thus, the system is analyzed from top to bottom, starting with an unexpected top event to individual failure modes. FTA can be graphically documented with Boolean expressions and offers a systematic treatment to combine the system effect with the failure mode. Many sources recommend using both FMEA and FTA to detect all the relevant types of errors in a system, [18, 19]. The main problem with FMEA and FTA is that the methods are subjective and can be subject to distortion. This can affect the analysis result and make it difficult to use as the basis for considering the stress rating.

By evaluating the linked elementary events, the reliability of the system is derived. The advantage of the fault tree analysis is the ease of describing complex systems. The failure probability ranking can be done in combination of statistical analysis.

D. Lifetime definition

In general, the lifetime of a component is defined as the length of time or the number of cycles a component will endure before a loss of primary function or an irreversible failure occurs. For hydraulic units the failures that may occur may be related to a number of internal sub components as illustrated in figure 2. These internal components are all subject to varying operating conditions, that directly affect the lifetime and wear of the components. The most important factor here is the lubrication properties between the different moving parts, which directly relates to pressure, speed, temperature and oil viscosity. Much of the work done in the area therefore relates to modeling and predicting the pressure distribution and the tribological properties in piston type machines, [20-22]. There is no research that directly links these properties to the lifetime calculation of these machines. On the contrary, lifetime calculations are typically done based on rule of thumb methods and experienced lifetime of components that dates back decades, [23, 24].

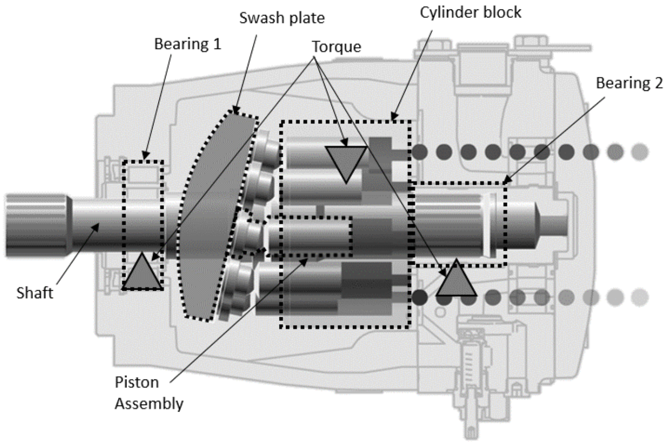

Fig. 2. Fatigue affected components of a pump.

III. KEY-COMPONENTS OF THE RESEARCH

Many devices used in mechanical systems consist of multiple components that all should function in order to carry out the overall function required of the device. Several of the components in the device may be subjected to alternating loads that may result in fatigue or other failures after a sufficient number of load cycles or time. Whilst the method described in this paper can be applied to any component system, this paper focuses primarily on axial piston units (pumps, motors). Hydrostatic units are ideal component systems for applying the methods described in this paper because they contain several fatigue life sensitive components.

The drivetrain referred to in this paper is a generic drive system consisting of one pump and one motor integrated into a vehicle in field. As shown in figure 3, the system includes among others a pump kit, a motor kit, and different bearings as wear-affected components.

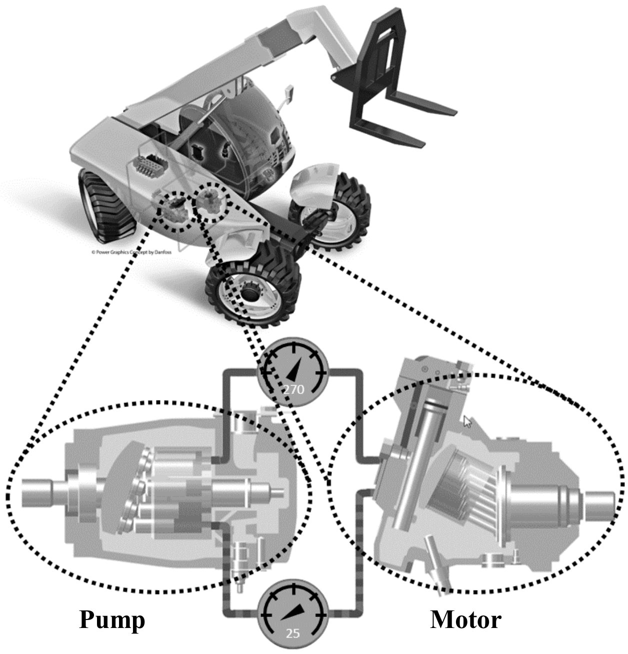

Fig. 3. Pump and motor system.

The material presented in subsequent sections requires a basic understanding of the basic components and functions of a drivetrain as shown in figure 2. Each rotating group in the axial piston unit includes nine piston assemblies, a cylinder block, and several other components required for proper kit function. The pump kit's cylinder block is splined to the pump shaft and the motor kit's cylinder block is assembled to the motor shaft. The piston assemblies in each kit move in and out of the nine block bores as the block rotates. Each piston assembly consists of a piston and slipper, which are joined together with a ball and socket joint. The slipper is allowed to move at an angle relative to the piston axis up to a maximum value. This free movement is critical to the function of the kit because, as each piston assembly revolves around the shaft axis, its slipper runs against a flat surface that is tilted relative to a plane of the shaft axis. The amount of tilt is equal to the angle of the swashplate. The pump swashplate is infinitely variable between two extreme positions (+18 degrees, -18 degrees). The angle of the motor can be up to 32 degrees.

The drivetrain is a system that converts mechanical (shaft) power into hydraulic power and back to mechanical power. Assuming the pump swashplate is at some angle, the piston assemblies in the pump kit reciprocate in and out of their respective bores and, in the process, each in turn receive and pump hydraulic fluid. The fluid that is pumped is sent to the motor kit, where pressurized fluid drives the motor piston assemblies out of the block and against the motor shaft. The motion of the pistons causes the motor kit and shaft to rotate. The opposing load (torque) acting on the motor shaft resists this rotation, but as long as the pressure of the fluid is sufficient in overcoming this opposing torque, the pistons will move out of the block and the motor shaft will rotate.

At any given instant, some of the pistons in both kits are at high pressure and some are at low pressure. For the pump, the high-pressure pistons are those that are moving into the block, pumping fluid to the motor kit. Simultaneously, the other pump pistons are receiving low-pressure fluid from the motor kit. In the motor, pistons moving out of the block bores receive high-pressure fluid and pistons moving into the bores return low-pressure fluid back to the pump kit. The difference in pressure between the two fluid paths is defined as the system's delta pressure. Since the pressure in the low-pressure portion of the hydrostatic loop is usually maintained with a separate charge pump, it is also referred to as charge pressure. It is also called the low loop pressure because it corresponds to the low-pressure side of the hydrostatic loop, [25].

IV. Addressing Of The Issues

The state of the art study is concentrated on the common lifetime calculation methods of drivetrains in off-road field. The analysis of the state of the art shows three clear aspects which do prevent the required accuracy. At first, the user has to accept a certain distribution range. Depending on the used distribution method and on used reliability percentage, the calculation can be adjusted. The adjustment can be misinterpreted or give the space for modifications of the lifetime results. The second aspect covers the load-dependent treatment only. As the state of the art analysis shows, the load is only one lifetime-influencing factors among others. For a complete picture, factors like temperature and oil viscosity should be included as well. The third aspect covers the calculation based on a "short cut" of the load life. Typically, just one shortly recorded load cycle will be used as the load spectrum. Thus, a driver records the data of a typical operation cycle. Mostly the data are incomplete because it covers just an ideal/standard operation cycle without any additional information like transport of the vehicle from point A to B or low idle stay-time. A data acquisition of a long period does provide a better overview of the real load on variable condition. To know the load on variable condition is very important because it gives the possibility of stress rating analysis in different operation phases like driving- or working-mode.

Therefore, it is required to know a lifetime L under variable load condition. Due to the fact that this work is focused on the load life, the research will cover among others: the speed, the load and displacement angle investigation. In this relation the following basic lifetime equation, with generic exponents, has been proposed, [16]:

$$L = \left(\frac{C}{P}\right)^k \tag{3.1}$$

According to the Weibull and WeiBayes method, the lifetime prediction can be calculated with reasonable certainty using the confidence factor a_c, which gives the lifetime L_x with expectation of x % failure probability under operating conditions:

$$L_x = a_c \times \left(\frac{C}{P}\right)^k \tag{3.2}$$

It should be noted that the confidence factor is determined based on the ideal calculated lifetime and related to the load life design/size/material value. The load spectrum is given by load-related values.

Due to mismatching of the lifetime calculation values (resulted from current calculation method) relative to the real lifetime (test lab proved) in past years, development departments are forced to verify the calculation results by time consuming testing. This leds to the new makeshift method of lifetime calculation plus testing. This currently used method is utilizable as a solution with high effort and cost and should be replaced by better and more accurate calculation methods.

Based on e.g. the work of Lorösch [5-6], it is known that the simple (load dependent only) treatment of the lifetime equation is not good enough. Thus, an extension of the equation is needed:

$$L_{x,mod} = \prod_{i=1}^{m} \left(\frac{C_i}{P_i}\right)^{k_i} \times \prod_{j=1}^{n} a_j \tag{3.3}$$

The above expression shows the extension of the new approach. Hence, the influencing factors should be investigated and researched.

The load effects will be investigated on each subcomponent of the axial piston units. Thus, in combination of load chain inside of the system (see figure 4) with the investigation of the lifetime exponent of each subcomponent will be researched. For determining of each subcomponent's fatigue characteristics information about the components load life curves are required. However, these curves are generally difficult to achieve or not up to date. This creates the requirement to collect the data in field, which will be significant for the complete work.

Each component of the pump and the motor is affected by loads in different form like pressure and speed, etc. The process forces and the interaction between unit components lead to fatigue and material stress. The detailed part of a calculation model of a piston assembly is illustrated in figure 4, which shows the high-level loads acting on the piston assembly. Here, different methods will be applied for the lifetime prediction. The target is to analyze a load related system step by step. Hence, a calculation model of a drivetrain (physical model) will be extended with lifetime-impacted factors. The approach will be the analysis of every single subcomponent, including piston, bearing and cylinder block with regard to life determining factors. This will be done based on detailed duty cycles and determination of load rating as well as on qualitative methods like FTA methods. Calculation methods like Weibull and Bayesian statistics will also be helpful to get the first results. Wherever, the deviations of current calculation will be investigated and improved. All these unit component results will then be merged together to a single system calculation model. The analysis of the whole system includes the detection of the weakest components as well.

As an example, a component analysis of the piston assembly is rough illustrated in figure 4. Similar analysis will be made for all other subcomponents, based on the determined load data. These sub-analyses will then be the foundation for a combined system formulation for the expected component lifetime. Hence the way in which the influence factors should be evaluated depends on influence size as well. In general, the approach should lead to the derivation of an improved calculation methodology of the whole system (pump or motor).

V. Conclusion

The drivetrain suppliers are continuously working on the improvement and adaptation of products to meet the needs of an evolving market. Nevertheless, an investment of time for costly- and resources-consuming endurance tests is required, in order to verify the calculated lifetime and to confirm needed accuracy. In different product development cases like maintenance or design, it is important to understand clearly, how reliable is a product. Hence, each event which does exceed the predicted lifetime, has dramatic consequences in different forms of unpredicted cost. Whilst the inefficient use of lifetime leads to uneconomic product, key word: unused resources. Therefore, the expectation of the customer on the reliability of predicted lifetime is very high.

The state of the art investigation shows that the calculation of the lifetime based on load life cannot be accurate enough. Different literature sources show the disadvantages of the load-based treatments. A method which is based on one lifetime-influencing factors of many cannot deliver the needed accuracy. Thus, caused by the outdated “state of the art” method and knowledge gaps of the existing load life in field a research of a new lifetime calculation revision is more than needed. Moreover, many new statistical methods like FTA do exist in the meantime, which can support the lifetime prediction. Different new methods can be matched together as verification of used methods or as extension to get higher accuracy. As well, new possibilities to measure the data with higher resolution and transfer the field data to a data base in a simple way, deliver new tools for the data acquisition.

The chosen research path of load chain with extended lifetime factors will provide an improved calculation method with more accurate result. The load chain calculation model, design treatment and statistical methods do expand the load-life-based approach to a complete picture of lifetime prediction. The subcomponent characteristic (material and design values) and load behavior will be combined to the system view of the whole drivetrain. Thus, the subcomponents equations will be merge together to system equation. The solution adopted here will deliver a new revision of the lifetime calculation method.

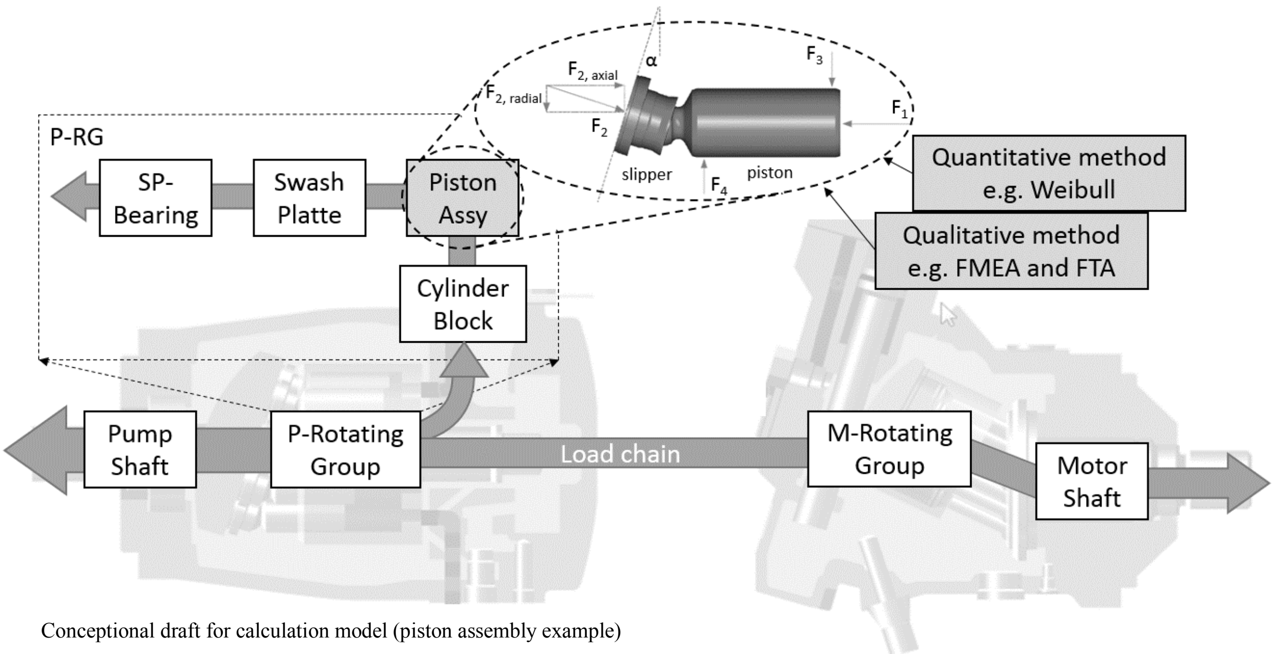

Fig. 4. Conceptional draft for calculation model (piston assembly example)

VI. OUTLOOK

Starting with the integration of a data measurement and collecting system into drivetrain, the data investigating is in focus of the first research steps. This includes also the general phase of development and implementation of the measurement system. In this case, different applications are already selected and specified. Hence, applications like e.g. wheel loader or combine are in focus. Currently expected measurement and clustering concepts include a system with microprocessor based data collection and data transfer via wireless communication or via data logger.

The research focus of the next phase will be on the load spectrum investigation of axial piston units. As mentioned in the state-of-the-art chapter, load spectra of the field should be investigated. Thus, a profile classification will be on relevant values that have significant influence on component lifetime like maximal drive speed, load peaks, working phase, etc. One classification type may be an application with constant operation speed. All these profile classes have a specific influence on the drivetrain system. In this case, key values such as pressure, speed, displacement angle and temperature will be measured and clustered. The mostly used load clustering is pressure over engine speed (with resting time in the Z-axis), see illustrative examples in figure 5:

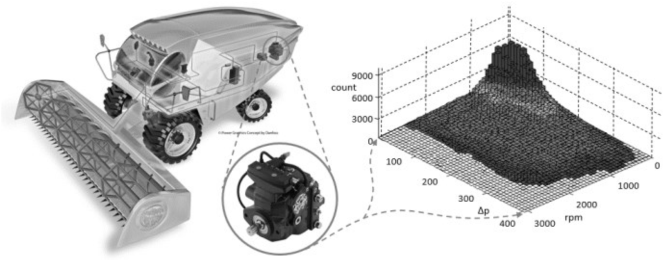

Fig. 5. Load spectrum (illustrative example)

Impacted by design, load and failure rates, the focus of the new calculation method is on improved accuracy of the lifetime prediction. Hence, the drivetrain supplier may fix the lifetime value and change / optimize the design in a more targeted way. The outcome of this work is therefore intended as a new calculation method, which will derive an improved prediction of lifetime. The implementation of the new calculation method and verification phase will be iterative with some degree of overlap, caused by cross checks of calculation and testing results.

Finally, the success criteria of this work will be verified by the required testing expenditure. This will lead to discussion of today's lifetime testing specifications and derivation of an improved specification (improved in terms of accuracy and test duration). This will have the positive side effect of reduced expenditure on testing, whereas today's lifetime testing involves a lot of time and resources. The work will be finalized after the verification of the improved calculation method.

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